

# Future Neutrino Physics Building on a Legacy

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# Outline

1. The Neutrino Legacy & Beyond
2. Very Long Baseline Neutrino Oscillations and Proton Decay (A Marriage Made in Brookhaven)
3. BNL-Homestake 2540km or FNAL-Homestake 1300km  
Very Large Detector (300kton H<sub>2</sub>O, 75kton LAr, Hybrid)  
Proton Decay,  $n-\bar{n}$  osc. Supernova  $\nu$ , Atm.  $\nu$ , ...  
Leptonic CP Violation,  $\theta_{13}$ , Mass Hierarchy...  
Fermilab Project X (8 GeV Linac + MI)  $\rightarrow$  2MW
4. Concluding Remarks

# 1. The Neutrino Legacy and Beyond

- 1930 Pauli Postulates Neutrino (“Neutron”) Existence
- 1932 Chadwick Discovers The Real Neutron
- 1933 Fermi Renames Neutrino-Develops Weak Int.
- 1956 Reines & Cowan Discover  $\bar{\nu}_e$  (reactor)
- 1958 Goldhaber, Grodzins and Sunyar:  $\nu$  Helicity (V-A)  
(also G. Feinberg IVB loop  $\rightarrow B(\mu \rightarrow e\gamma) \approx 10^{-4}!$ ?)
- 1962 Lederman, Schwartz, Steinberger Discover  $\nu_\mu$
- 1977 Perl Discovers  $\tau$  lepton  $\rightarrow \nu_\tau$  (later directly obs.)
- 1983  $W \rightarrow e\nu_e, \mu\nu_\mu, \tau\nu_\tau$  directly observed at CERN
- 1991  $Z \rightarrow \nu\bar{\nu}$  at LEP (3 neutrino flavors)
- (+ contributions of many other people)

We have come a long way!

- 1969-90s Ray Davis Measures Solar  $\nu_e$  Flux at Homestake Deep Underground Mine  $\sim 1/3$  Expected (Bahcall Standard Solar Model)  
Gallex, Sage, SuperK, SNO, Kamland (Reactor)  
solar  $\nu_e \rightarrow 1/3 \nu_e + 1/3 \nu_\mu + 1/3 \nu_\tau$
- 1980s IMB, Kamioka, measure atm.  $\nu_\mu$  flux, less than expected (Also observe supernova 1987a neutrinos!)  
SuperK, K2K (Accel.), MINOS (Accel.)  
atm.  $\nu_\mu \rightarrow 1/2 \nu_\mu + 1/2 \nu_\tau$

Neutrino Oscillations Established  $\rightarrow$  Neutrino Masses & Mixing Measured (Great Progress!)

## Neutrino Masses and Mixing (formalism & status)

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = U \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix} \quad (1)$$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$c_{ij} = \cos \theta_{ij} \quad , \quad s_{ij} = \sin \theta_{ij}$$

$$J_{CP} \equiv \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos \theta_{13} \sin \delta. \quad (2)$$

- $\Delta m_{32}^2 = m_3^2 - m_2^2 = \pm 2.7(3) \times 10^{-3} \text{ eV}^2$
- $\Delta m_{21}^2 = m_2^2 - m_1^2 = +7.6(2) \times 10^{-5} \text{ eV}^2$

(Recent very precise KamLAND Measurement)

$|\Delta m_{21}^2 / \Delta m_{32}^2| \approx 1/35 \rightarrow \text{CP Violation Exp Doable!}$

Hierarchy  $m_3 > m_1$  (normal) or  $m_3 < m_1$  (inverted)?

$$\theta_{23} \sim 45^\circ \quad \sin^2 2\theta_{23} = 1.0 \quad (\theta_{23} \text{ or } 90^\circ - \theta_{23})$$

$$\theta_{12} \sim 32^\circ \quad \sin^2 2\theta_{12} = 0.82$$

$$\theta_{13} \leq 11^\circ \quad \sin^2 2\theta_{13} \leq 0.15 \quad (\text{How Small?})$$

$$0 \leq \delta \leq 360^\circ ?$$

$$J_{\text{CP}} \approx 0.11 \sin 2\theta_{13} \sin \delta \quad (\text{potentially very large})$$

$$(J_{\text{CP}}(\text{quarks}) \approx 3 \times 10^{-5})$$

# What do we still need to learn?

- 1. Value of  $\theta_{13}$ ? (Daya Bay Reactor  $\sin^2 2\theta_{13} \rightarrow 0.01$ )
- 2. Sgn  $\Delta m_{32}^2$ ? (Important for Neutrinoless  $\beta\beta$  Decay)
- \*3. Value of  $\delta$ ?,  $J_{CP}$ ?, CP Violation? ([Holy Grail](#))
- 4. Precision  $\Delta m_{32}^2$ ,  $\Delta m_{21}^2$ ,  $\theta_{23}$ ,  $\theta_{12}$
- \*5. Lepton Number Violation (Neutrinoless  $\beta\beta$ )
- 6. Absolute Mass (Tritium  $\beta$  decay)
- 7. "New Physics" - Sterile  $\nu$ , Extra Dim., Dark Energy

## Osc. Goals: Measure all $\nu$ parameters.

- $\Delta m_{32}^2 = m_3^2 - m_2^2 = \pm 2.6(3) \times 10^{-3} \text{eV}^2$  to  $\pm 1\%$
- $\Delta m_{21}^2 = m_2^2 - m_1^2 = 7.6(2) \times 10^{-5} \text{eV}^2$  to 5% appearance
- $\sin^2 2\theta_{23} \approx 0.9 - 1.0$  to  $\pm 0.01$  (**Break Degeneracy**)
- $\sin^2 2\theta_{12} \approx 0.82 \pm 0.10$  to  $\pm 0.03$  (?)
- $\sin^2 2\theta_{13} \approx 0.15 \sim 0.003$
- Sign of  $\Delta m_{32}^2$
- $\delta$  to  $\pm 15^\circ$  (CP Violation)
- Sterile  $\nu$ , Extra Dim, Dark Energy? ...

Why do we care so much about:

Leptonic CP Violation?

&

Lepton Number Violation?

## Leptogenesis: Matter-Antimatter Asymmetry

- More baryons than antibaryons in our Universe

- Leptogenesis Scenario:

1. Heavy Majorana Neutrinos Created and Decay

$N \rightarrow H^- e^+, H^0 \bar{\nu}$  (L & CP VIOLATION)

Leads to antilepton (excess)-lepton Asymmetry

2. Electroweak Phase Transition (250GeV)  
(Baryogenesis)

't Hooft Mechanism B-L Conserved (B&L Violated)  
antilepton excess  $\rightarrow$  baryon (quark) excess by 1 in  $10^9$

Is L Violated in Nature? (Neutrinoless  $\beta\beta$  Decay)

Is there Leptonic CP Violation? ( $\nu$  oscillations)

Indirect evidence for Leptogenesis (Best we can do.)

Neutrino Physics May Be Responsible  
For Our Existence! (Baryons)

In More Ways Than One!

(Supernova - Heavy Elements)

We are the remnants of Supernovae

Very Long Baseline Neutrino Oscillations  
BNL-DUSEL 2540km or FNAL-DUSEL 1300km

- What (and where) is DUSEL?
- Homestake Gold Mine in South Dakota Chosen As Site For NSF Deep Underground Science And Engineering Lab (DUSEL). Expects ~ \$500M Funding. \$250M for Lab and \$250M for (first round) experiments.
- Currently \$5M/yr for 3 yr to develop proposal.
- Thanks to a generous benefactor Mr. Sanford (\$70M)

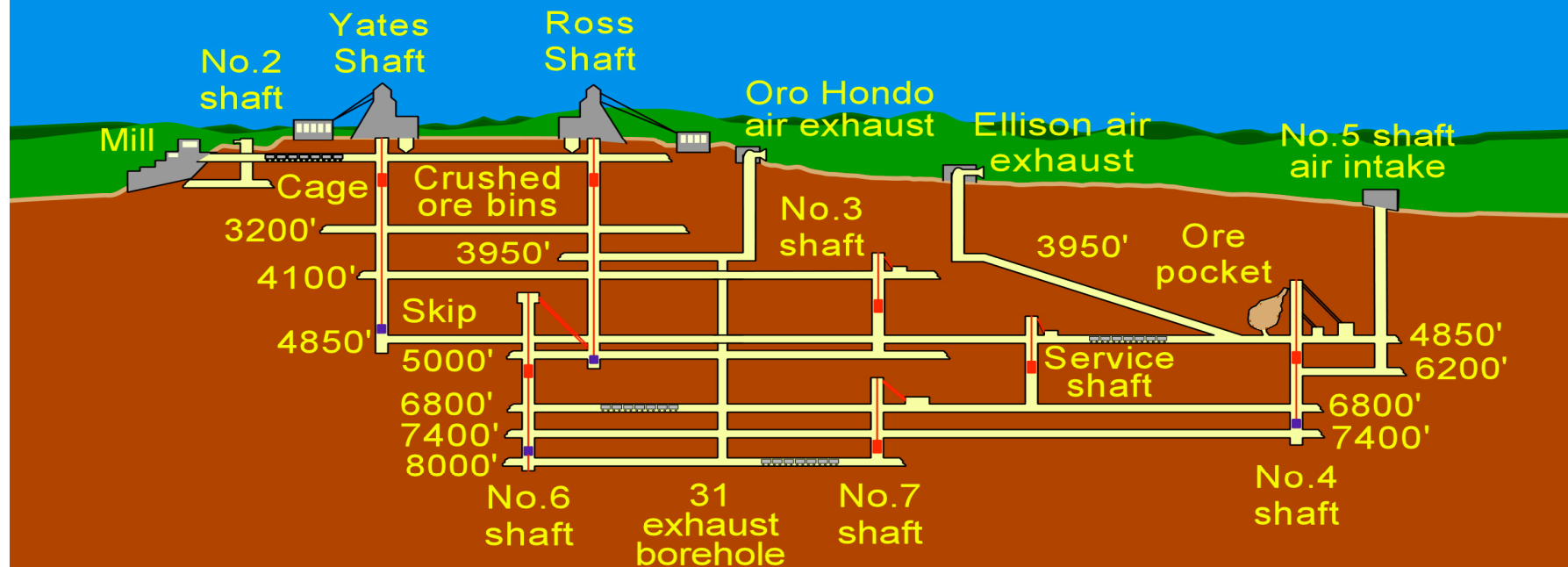
DUSEL  $\Rightarrow$  SUSEL

Director: J. Alonso

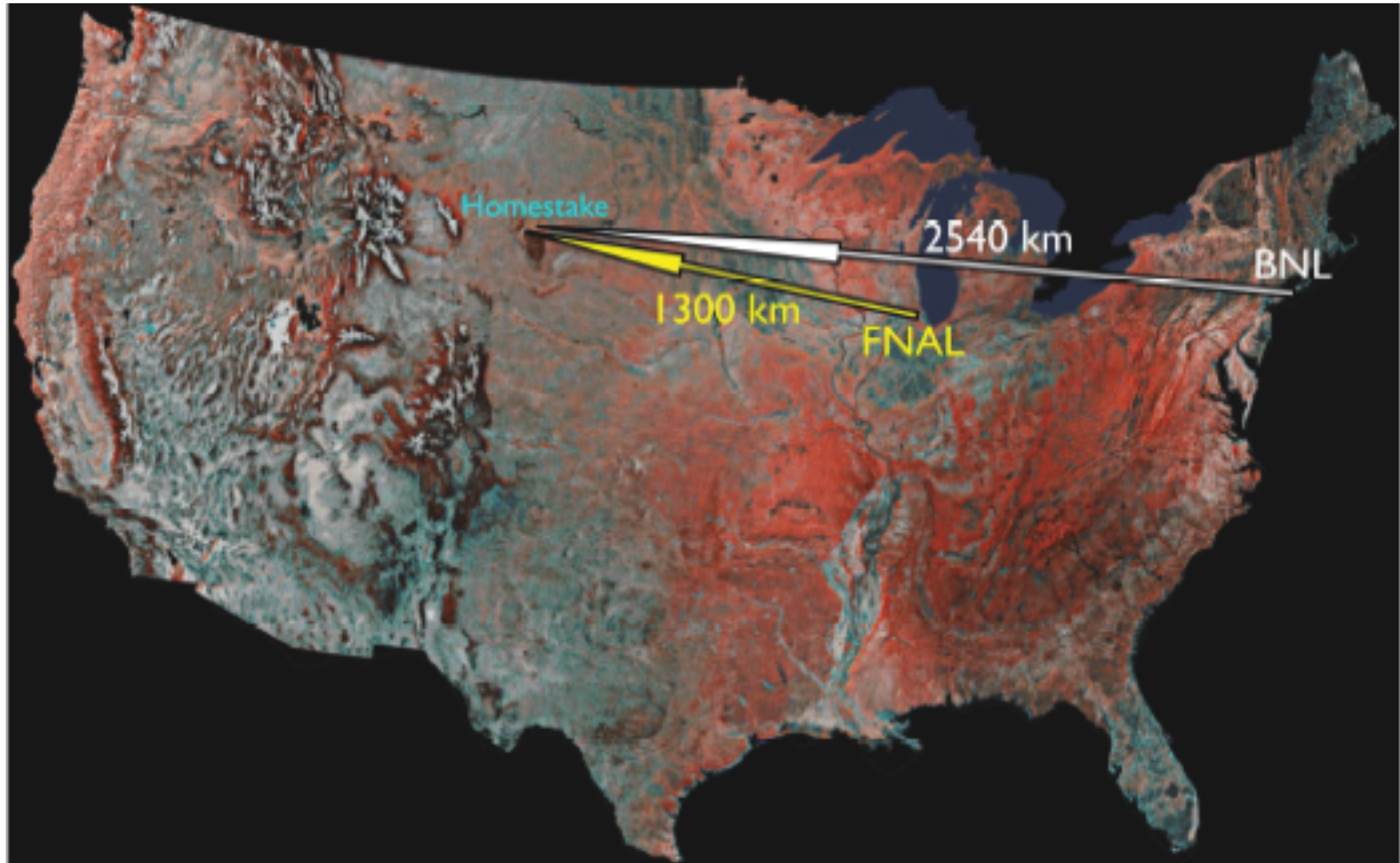
- Already has one Nobel Prize: Ray Davis Solar Neutrinos
- Expects to have neutrino oscillation program!



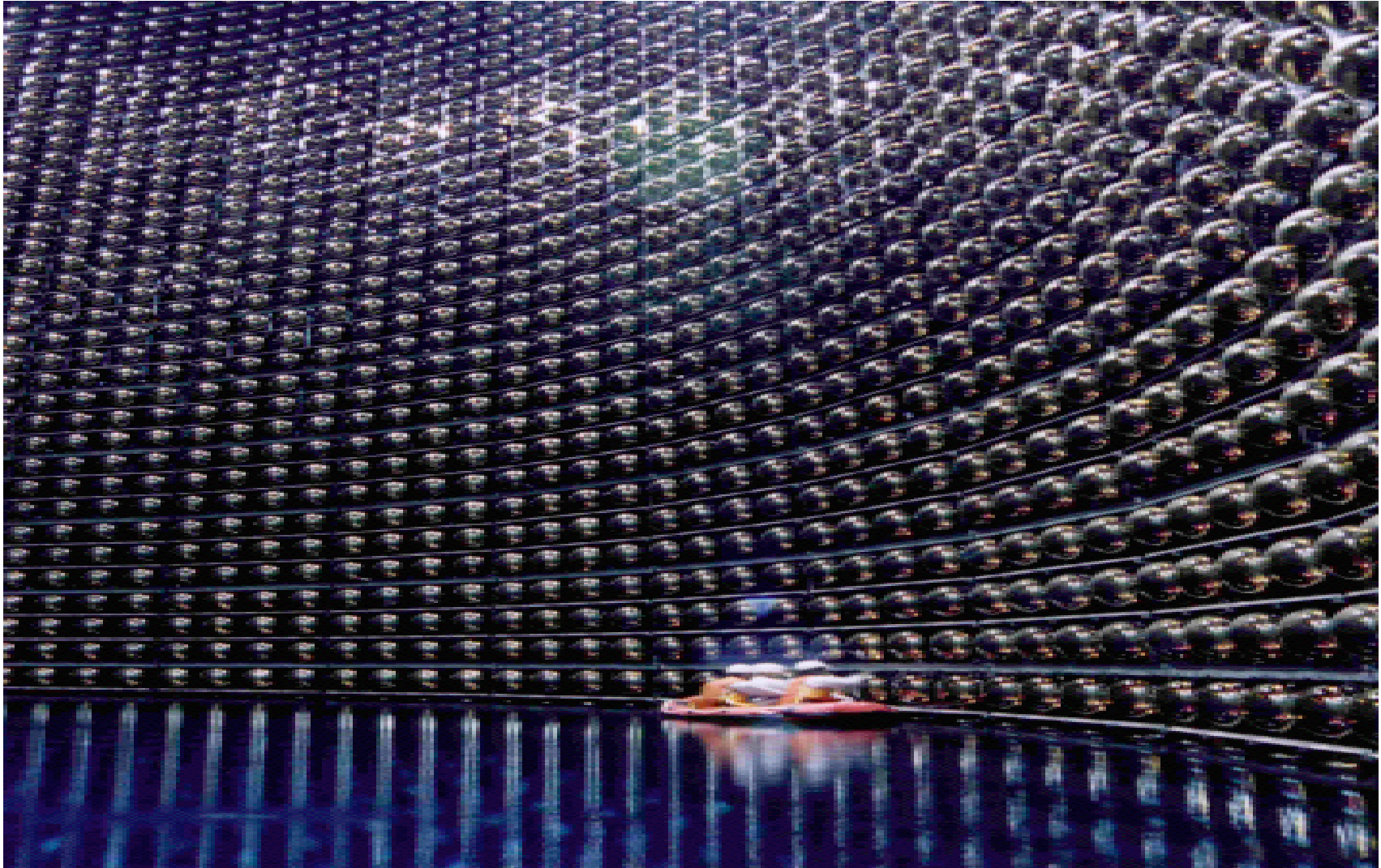
# General Homestake Mine Development



# Very Long Baseline Neutrino Oscillations (Fermilab or BNL- Homestake )



# SUPER KAMIOKANDE



## Leptonic CP Violation

$$P(\nu_\mu \rightarrow \nu_e) = P_I(\nu_\mu \rightarrow \nu_e) + P_{II}(\nu_\mu \rightarrow \nu_e) + P_{III}(\nu_\mu \rightarrow \nu_e) \\ + \text{matter} + \text{smaller terms}$$

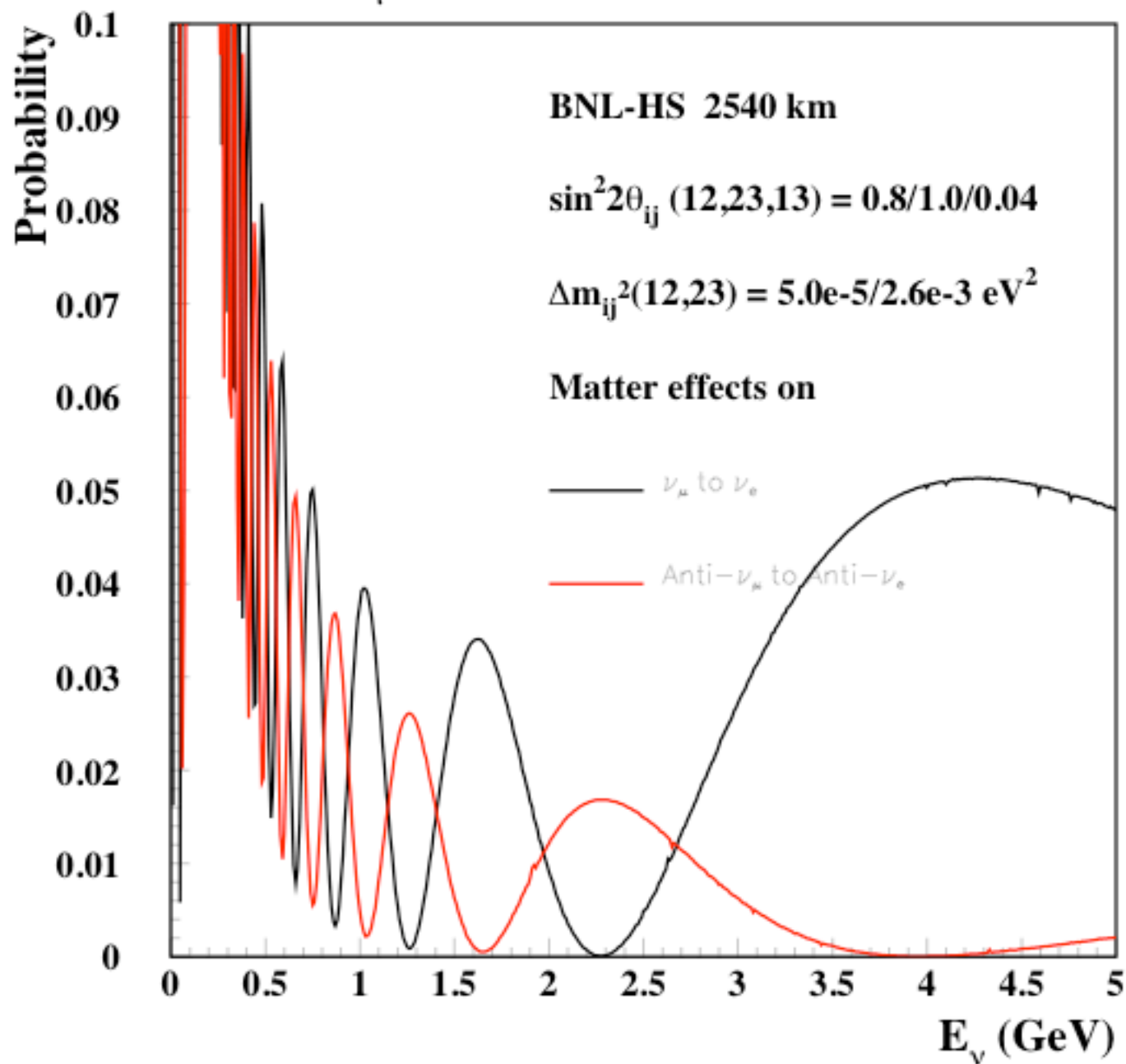
$$\mathbf{P}_I(\nu_\mu \rightarrow \nu_e) = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E_\nu} \right)$$

$$\mathbf{P}_{II}(\nu_\mu \rightarrow \nu_e) = \frac{1}{2} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos \theta_{13} \\ \sin \left( \frac{\Delta m_{21}^2 L}{2E_\nu} \right) \times \left[ \sin \delta \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E_\nu} \right) \right. \\ \left. + \cos \delta \sin \left( \frac{\Delta m_{31}^2 L}{4E_\nu} \right) \cos \left( \frac{\Delta m_{31}^2 L}{4E_\nu} \right) \right]$$

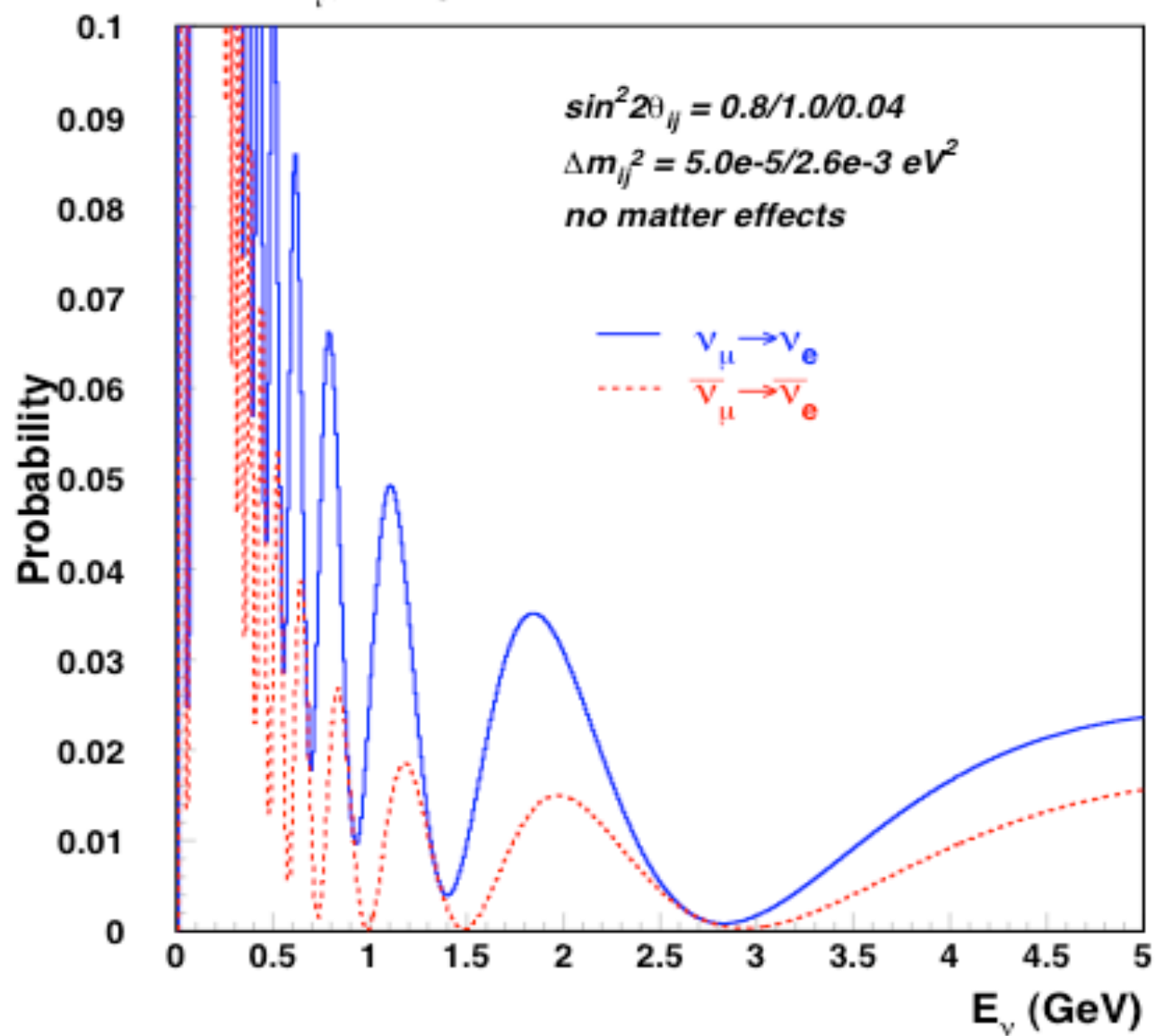
$$\mathbf{P}_{III}(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{12} \cos^2 \theta_{13} \cos^2 \theta_{23} \sin^2 \left( \frac{\Delta m_{21}^2 L}{4E_\nu} \right)$$

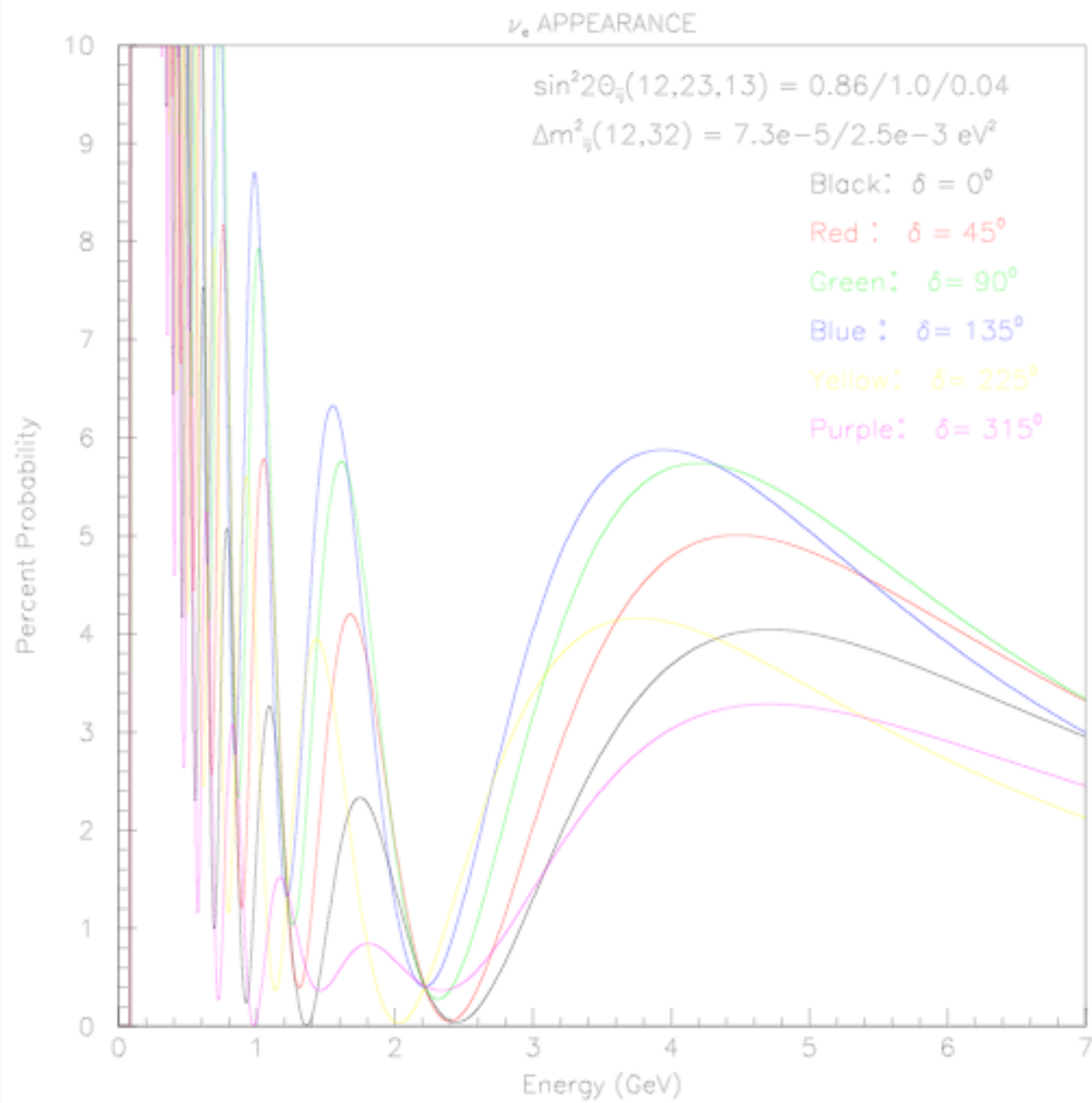
For antineutrinos,  $\delta \rightarrow -\delta$  and opposite matter effect.

# $P(\nu_\mu \rightarrow \nu_e)$ CP phase=45.

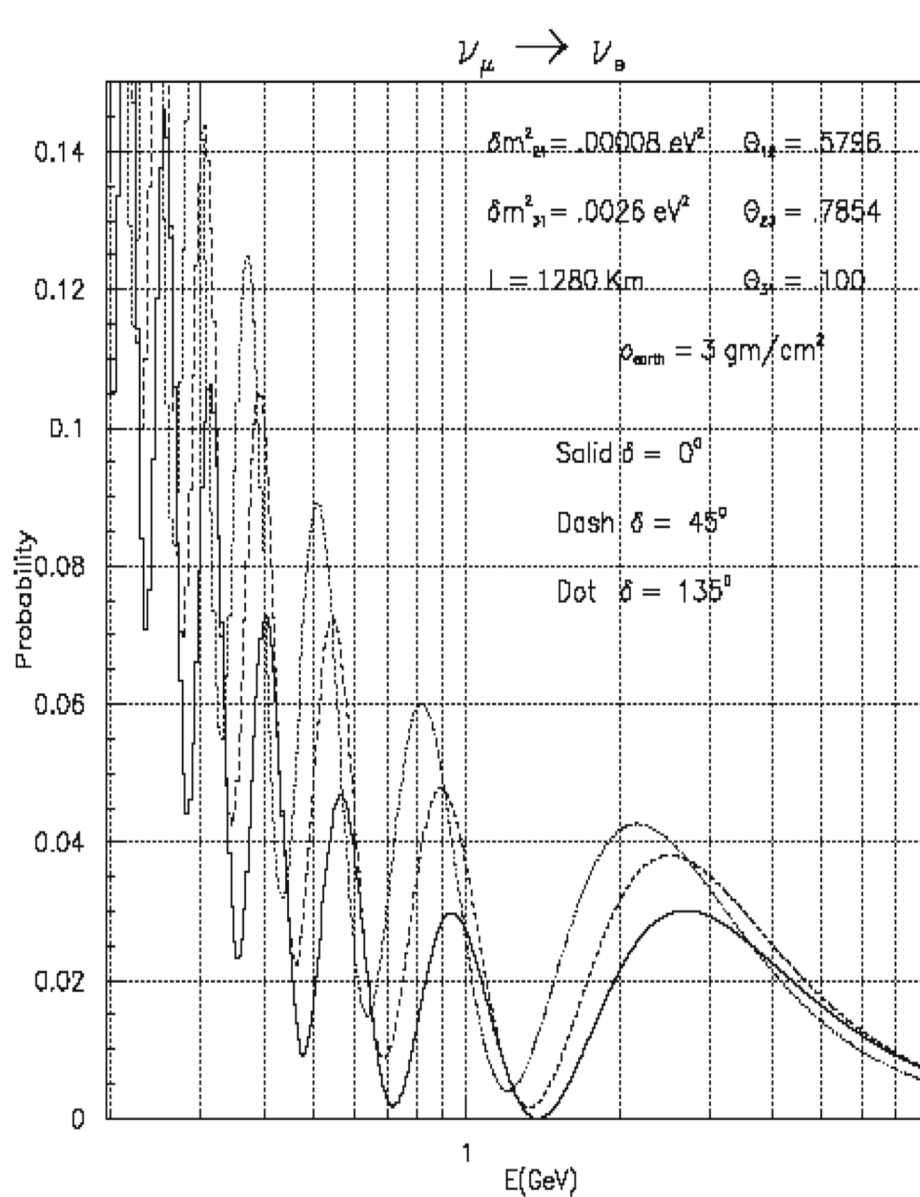


# $P(\nu_\mu \rightarrow \nu_e)$ with $45^\circ$ CP phase

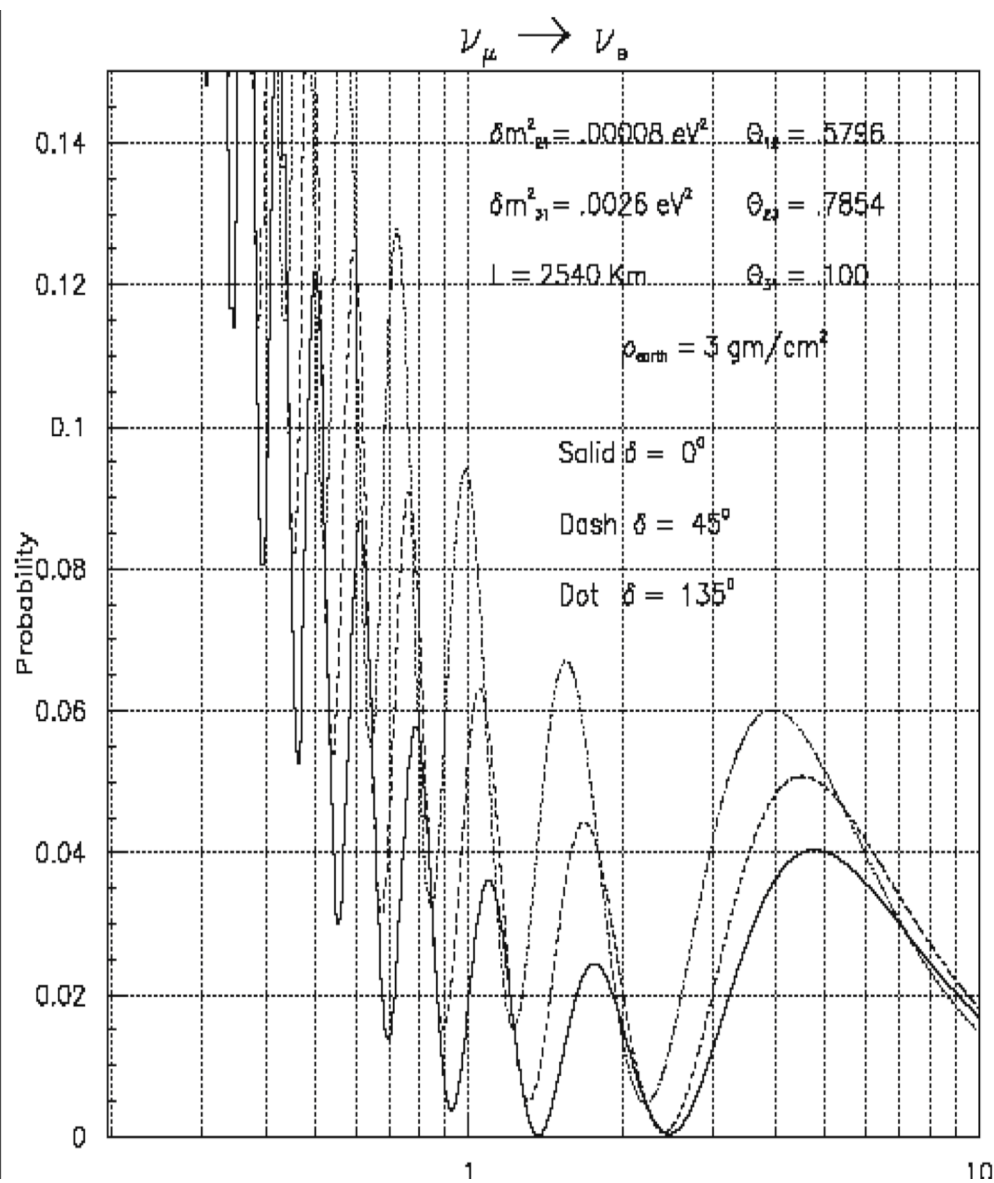




FNAL

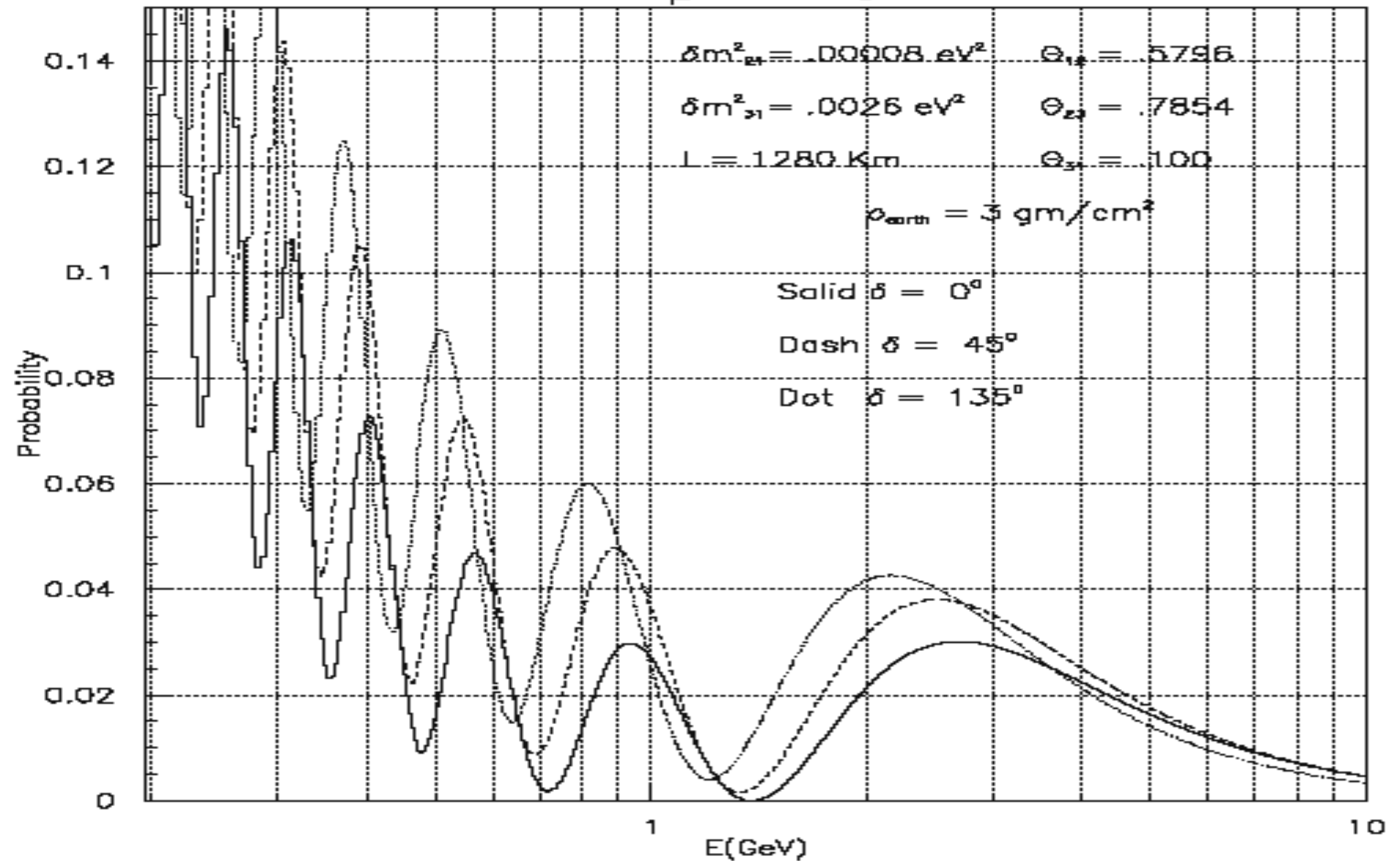


BNL



## FNAL

$$\nu_\mu \rightarrow \nu_\tau$$



# CP Violation Asymmetry

$$A_{CP} \equiv \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \quad (3)$$

To leading order in  $\Delta m_{21}^2$  ( $\sin^2 2\theta_{13}$  is not too small):

$$A_{CP} \simeq \frac{\cos \theta_{23} \sin 2\theta_{12} \sin \delta}{\sin \theta_{23} \sin \theta_{13}} \left( \frac{\Delta m_{21}^2 L}{4E_\nu} \right) + \text{matter effects} \quad (4)$$

$$F.O.M. = \left( \frac{\delta A_{CP}}{A_{CP}} \right)^{-2} = \frac{A_{CP}^2 N}{1 - A_{CP}^2} \quad (5)$$

$N$  is the total number of  $\nu_\mu \rightarrow \nu_e + \bar{\nu}_\mu \rightarrow \bar{\nu}_e$  events. Since  $N$  falls (roughly) as  $\sin^2 \theta_{13}$  and  $A_{CP}^2 \sim 1/\sin^2 \theta_{13}$ , to a first approximation the F.O.M. is independent of  $\sin \theta_{13}$ . Similarly, given  $E_\nu$  the neutrino flux and consequently  $N$  falls as  $1/L^2$  but that is canceled by  $L^2$  in  $A_{CP}^2$ .

## CP Violation Insensitivities

- To a very good approx., our statistical ability to determine  $\delta$  or  $A_{cp}$  is independent of  $\sin^2 2\theta_{13}$  (down to 0.003) and the detector distance (for long distance).

### iii) CP Violation Requirements

- Pick any reasonable  $\theta_{13}$  (eg  $\sin^2 2\theta_{13}=0.04$ )
- What does it take to measure  $\delta$  to  $\pm 15^\circ$  in about  $5 \times 10^7$  sec?

Answer (Approx.): [300kton Water Cerenkov Detector](#)

Approx 20% Acceptance,

75 kton LArgon 80% Acceptance

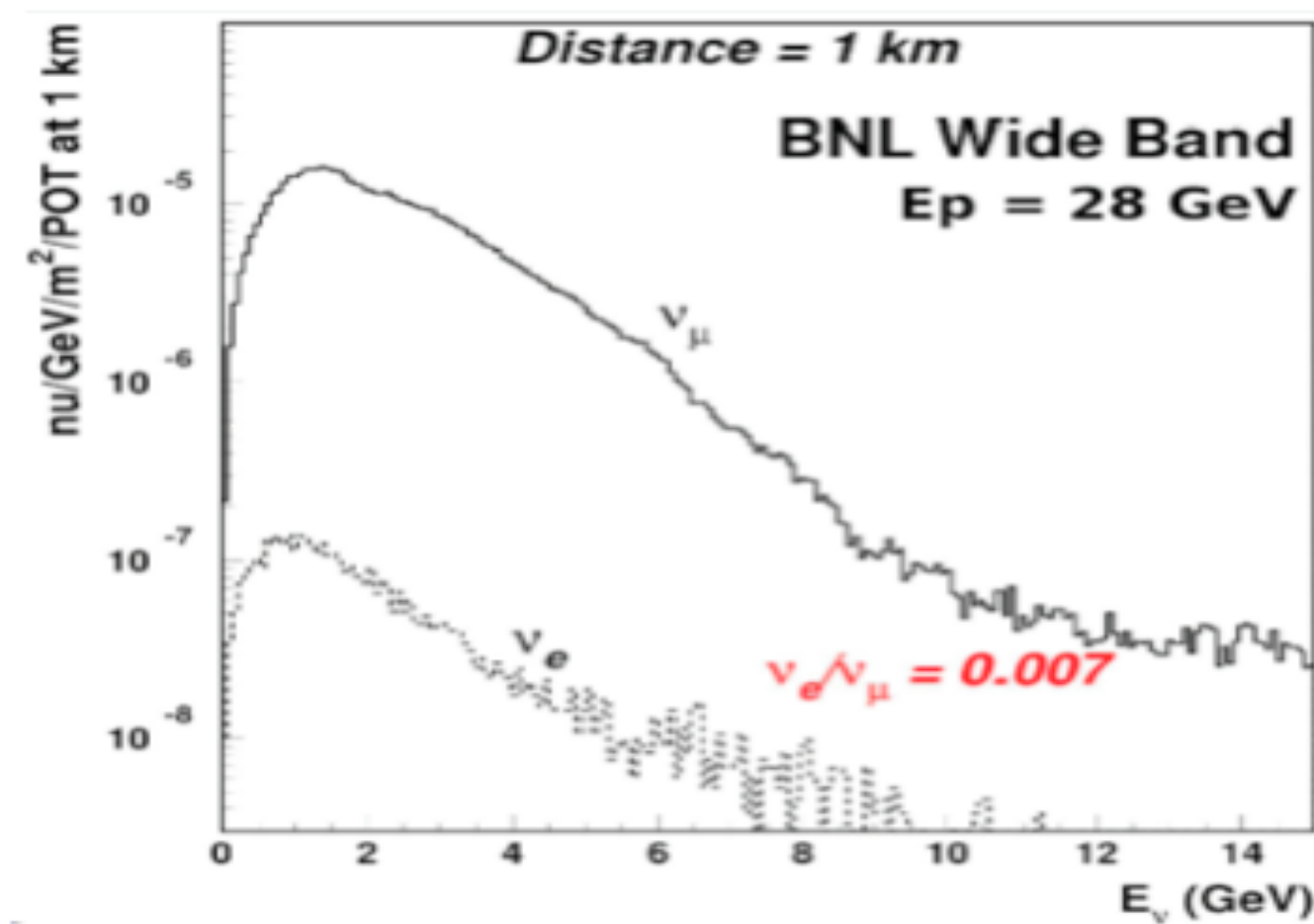
or Hybrid combination

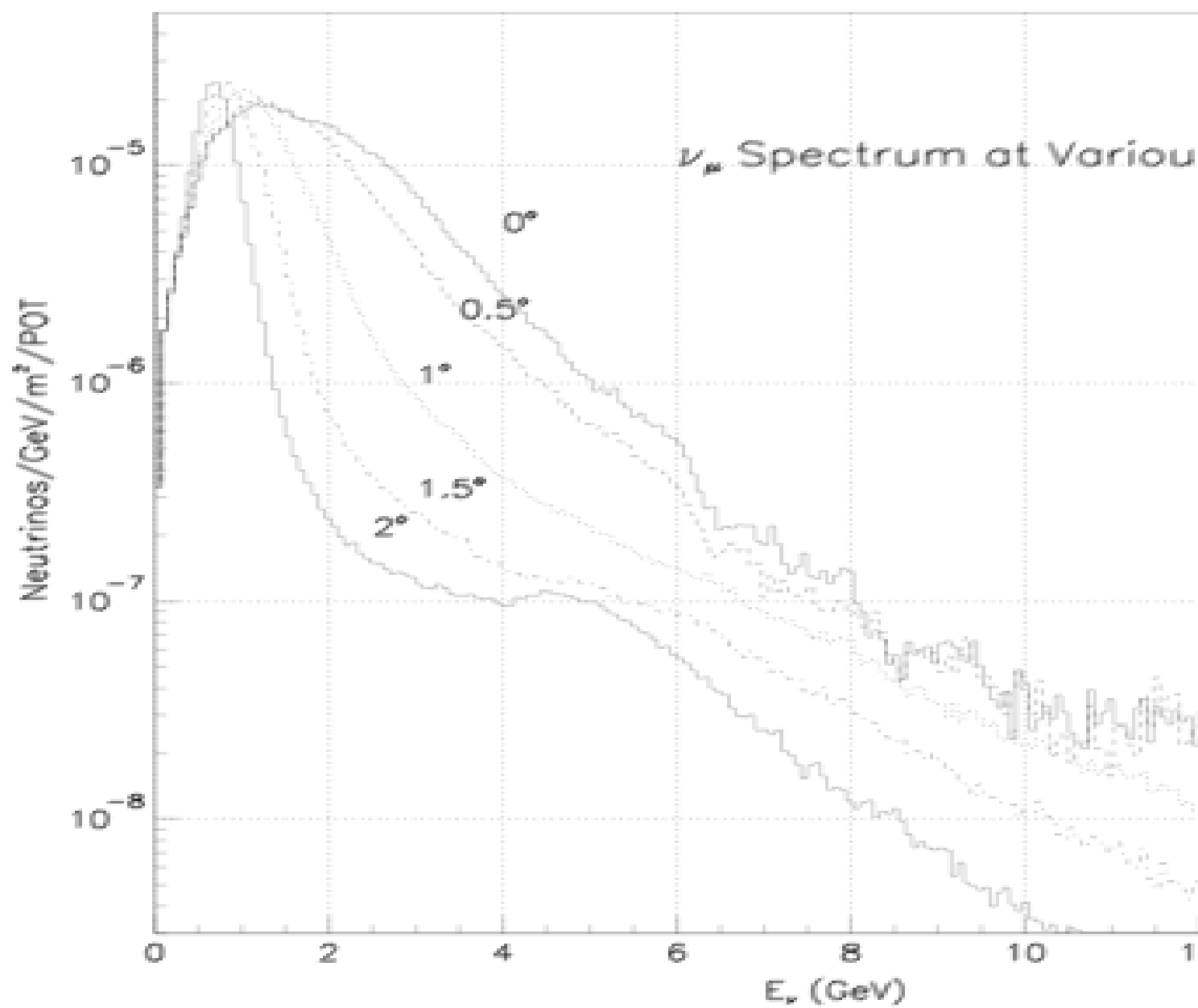
+ [Traditional Horn Focused  \$\nu\$  WBB](#) powered by  
[1-2MW proton accelerator](#) (AGS Linac Upgrade)

or

Project X with 2MW 50GeV protons  $\sim 0.5$  degree  
off-axis (don't need high energy  $> 3\text{-}4$  GeV neutrinos)  
(Very well matched to 300kton H<sub>2</sub>O Detector)

# Horn Focused Neutrino Beam

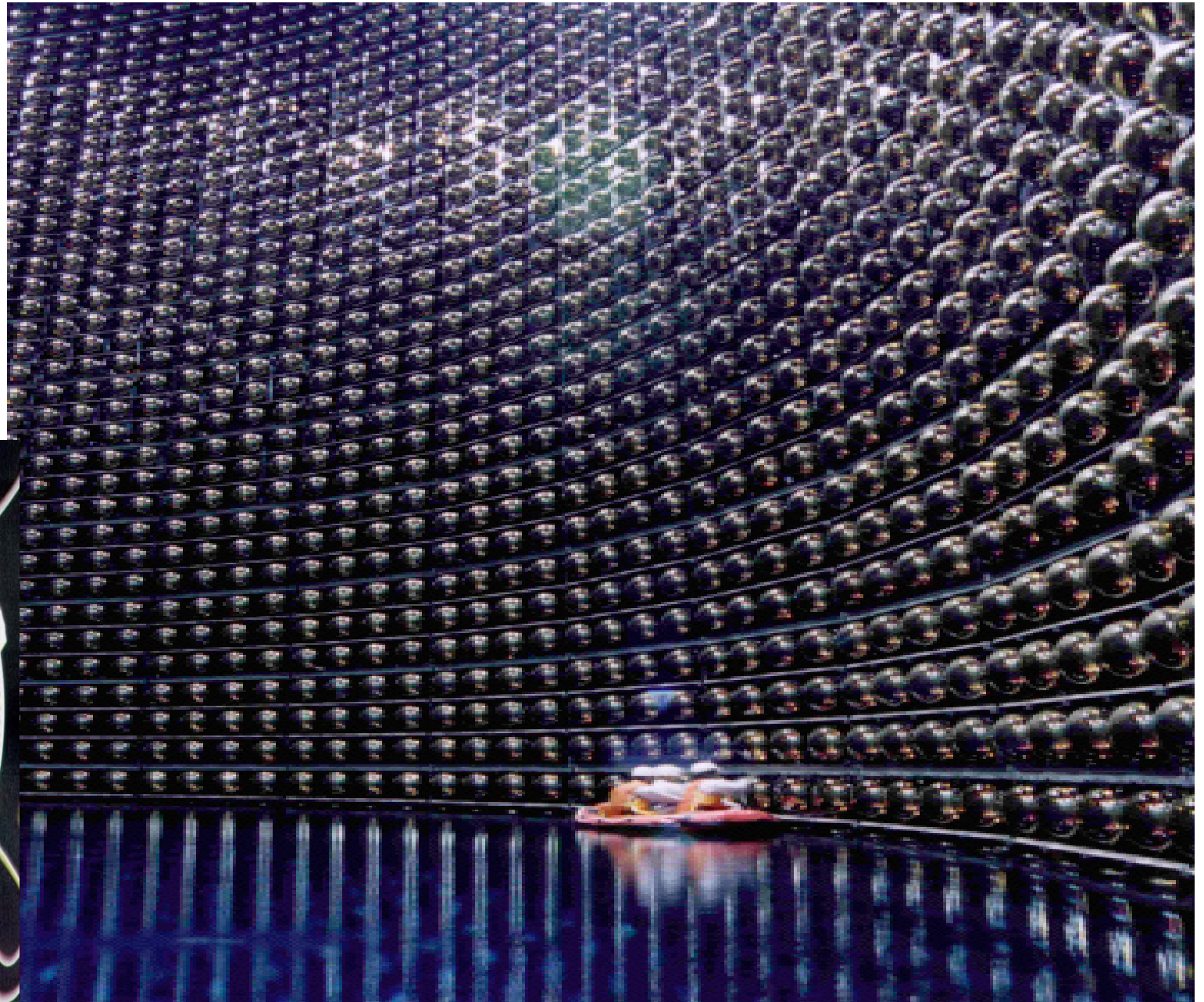
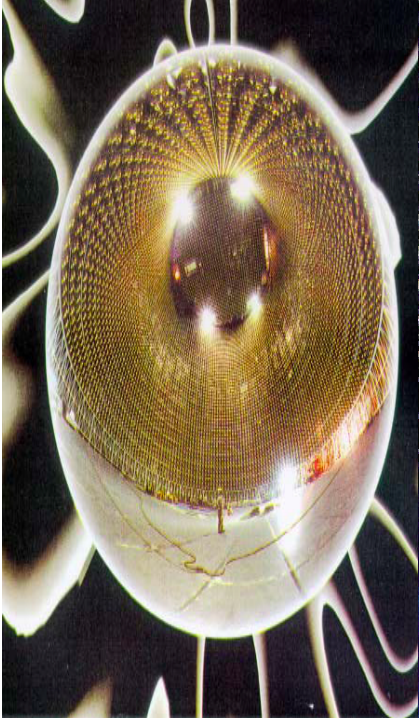
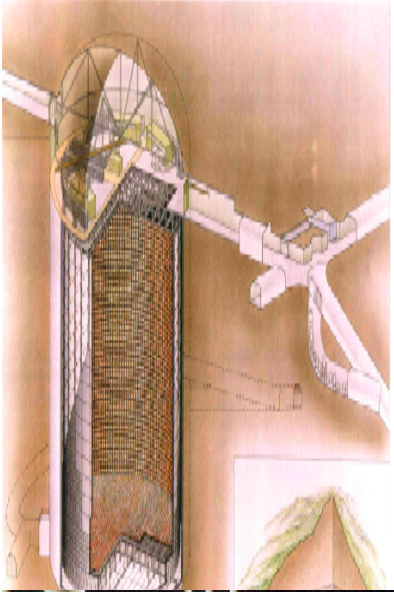




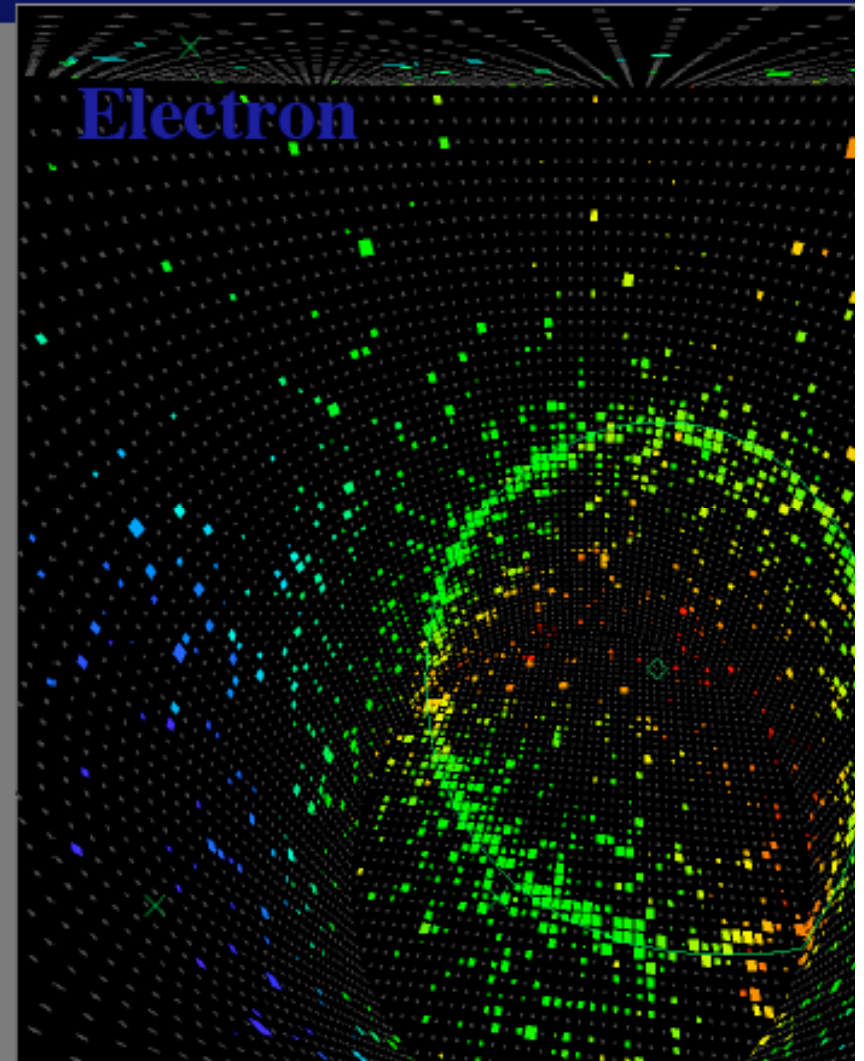
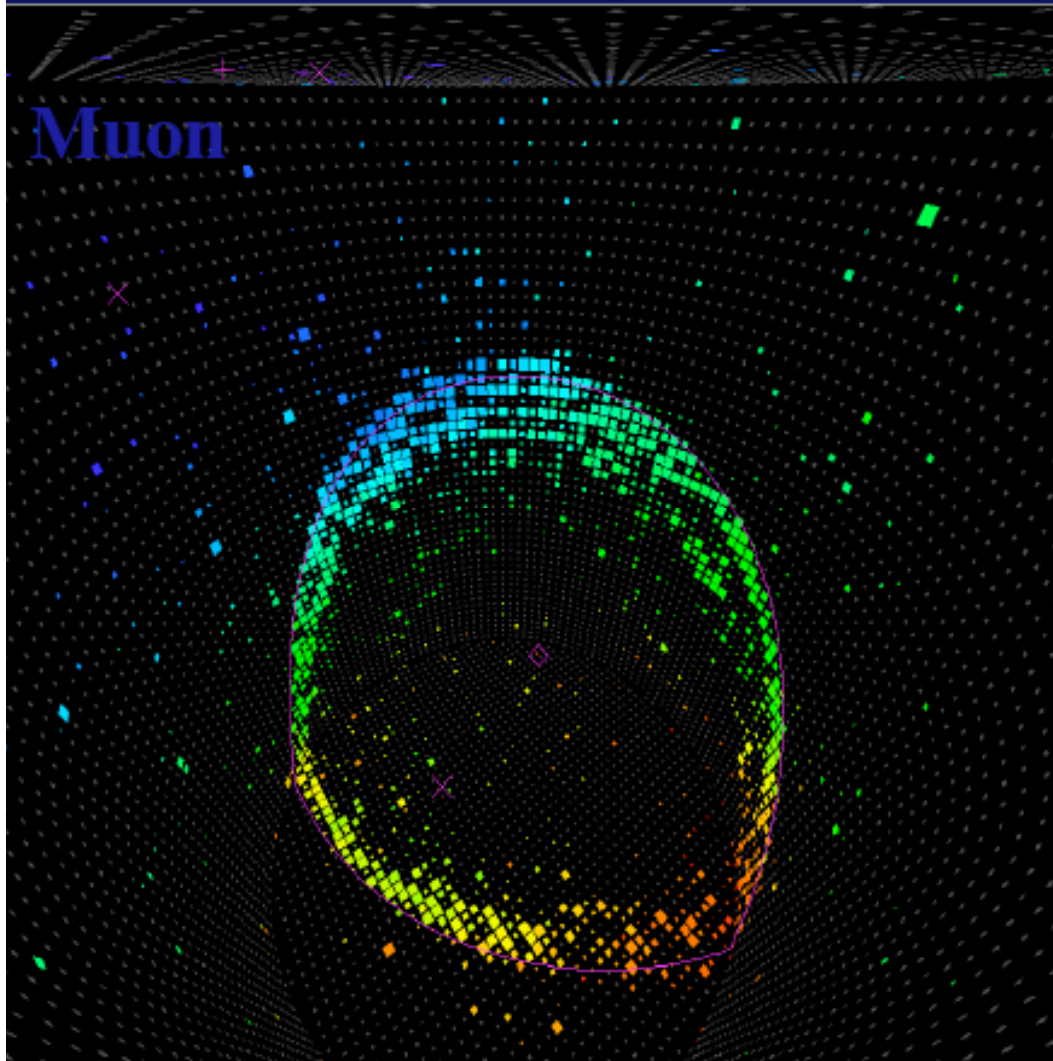
# Requirements

- 300-500 kton H<sub>2</sub>O (or equivalent)
- 1-2 MW proton beam (Superbeam)
- 3  $\nu$  + 3  $\bar{\nu}$  yrs running time
- Flagship of DUSEL
- Many Potential Revolutionary Discoveries (50yrs of Physics)

# SUPER KAMIOKANDE



# Particle Identification



# Physics Program (Big Underground Detector)

## i) Neutrino Physics (Osc., Astro., Cosmology)

Atmospheric  $\nu_\mu \rightarrow \nu_\tau$  osc (precision)

Solar  $\nu_e \rightarrow \nu_e, \nu_\mu, \nu_\tau$  (if needed)

\*Supernova  $\bar{\nu}_e, \nu_\mu \dots > 100,000$  events!

Relic Supernova  $\nu$  (History of the Universe)

### \*Very Long Baseline (Star Attaction) (Needs FNAL)

$$\left. \begin{array}{ll} \nu_\mu \rightarrow \nu_\mu & \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu \\ \nu_\mu \rightarrow \nu_e & \bar{\nu}_\mu \rightarrow \bar{\nu}_e \end{array} \right\} \text{Oscillations}$$

## Supernova Neutrinos

- SN 1987A: 19 events observed by Kamiokande & IMB

$\bar{\nu}_e p \rightarrow e^+ n$  **Great Discovery - Confirmed SN Models**

A SN in our galaxy (every  $\sim 40$ yr) at typical 10kpc would lead to about 100,000  $\bar{\nu}_e p \rightarrow e^+ n$  events/300kton  $H_2O$

Also,  $\nu e \rightarrow \nu e$ , ( $\nu = \nu_e, \nu_\mu, \nu_\tau, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$ )  $\sim 1000$  events

We would like to see  $\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}$  (initial burst)

$\sim 250$  events/kton LArgon

Neutrino Spectrum  $\rightarrow$  SN Dynamics & Oscillations

**Extremely Rich Discovery Possible**

**We must have as many detectors as possible online**

**Relic SN Neutrinos (10-40MeV) S/B/yr  $\sim 10/10$**

# $\nu_\mu$ Disappearance

## Neutrino Running

- Total exposure: 2500 kT.MW.( $10^7$ ).sec
- 195000 CC evts/6yrs: 2MW-FNAL, 100kT-HS
- Use only clean single muon events.

## Measurements

- 1% determination of  $\Delta m_{32}^2$
- 1% determination of  $\sin^2 2\theta_{23}$
- Most likely systematics limited.

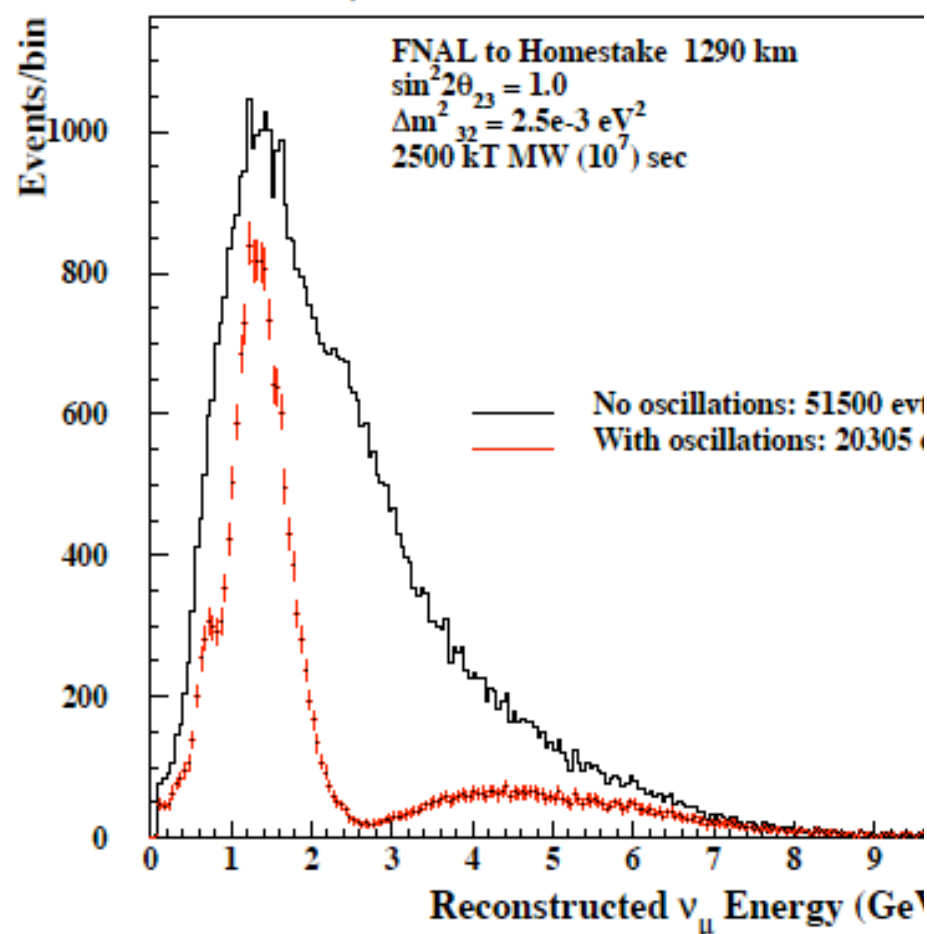
## $\bar{\nu}$ running

- Need twice the exposure for similar size data set.
- very precise CPT test possible.

Very easy to get this effect

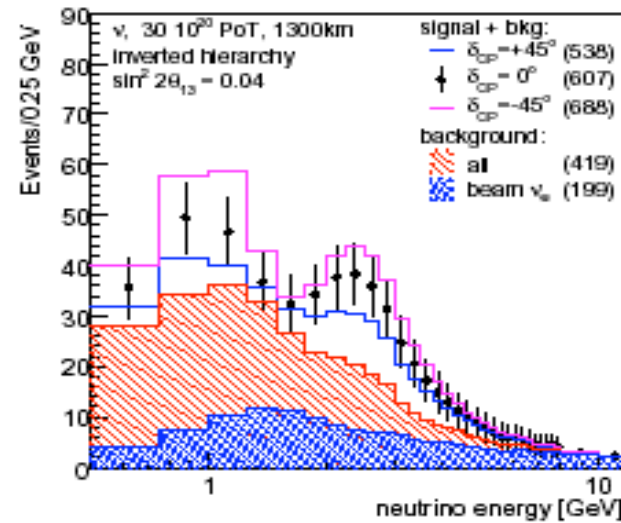
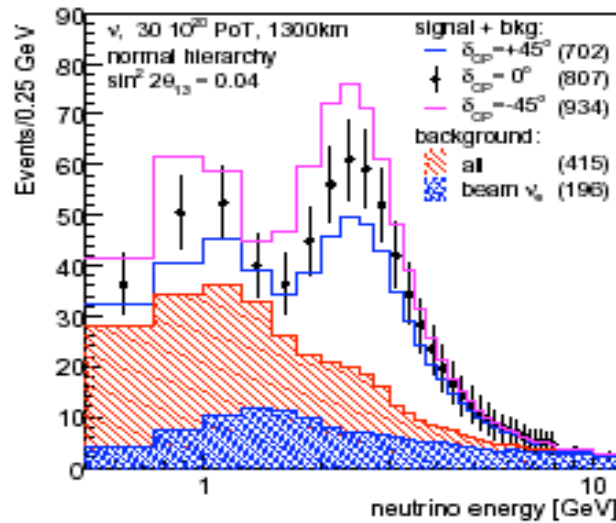
Does not need extensive pattern recognition. Can enhance the second minimum by background subtraction

## $\nu_\mu$ disappearance

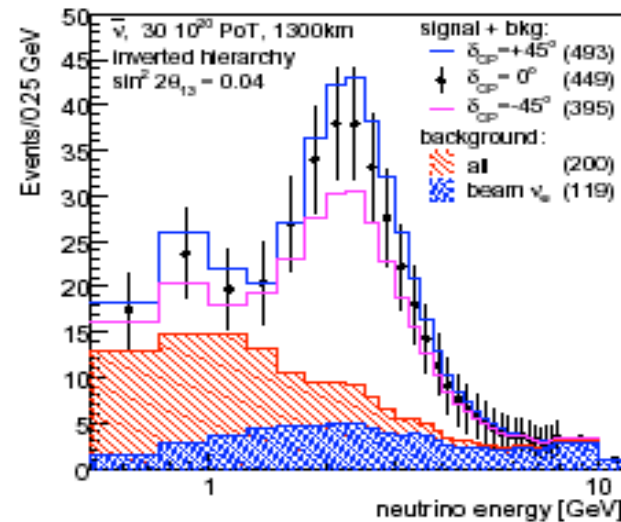
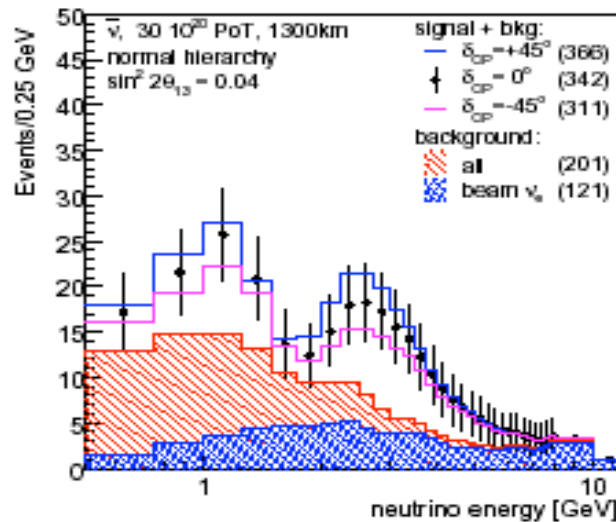


# Water Cerenkov: FNAL-Homestake

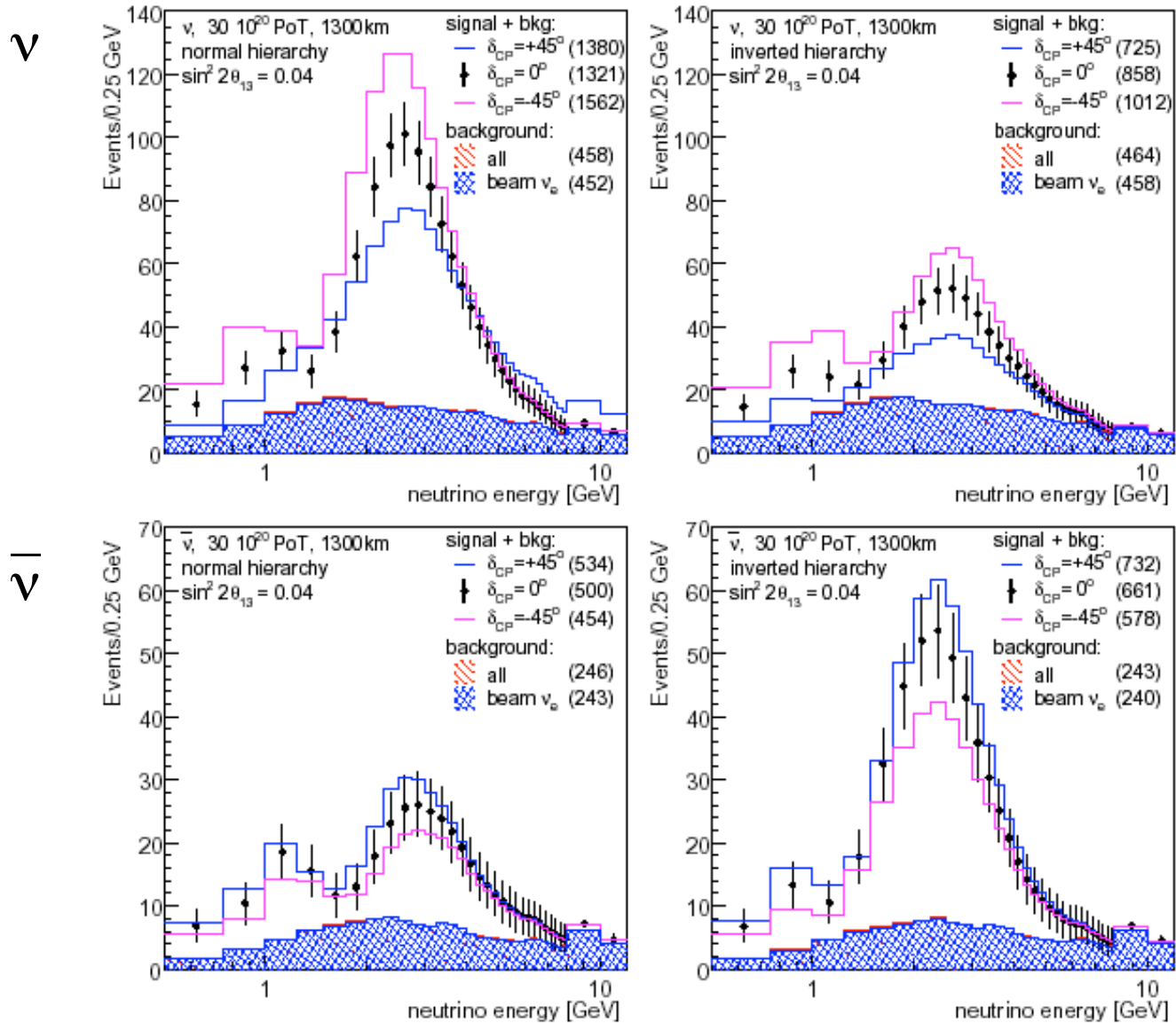
$\nu$



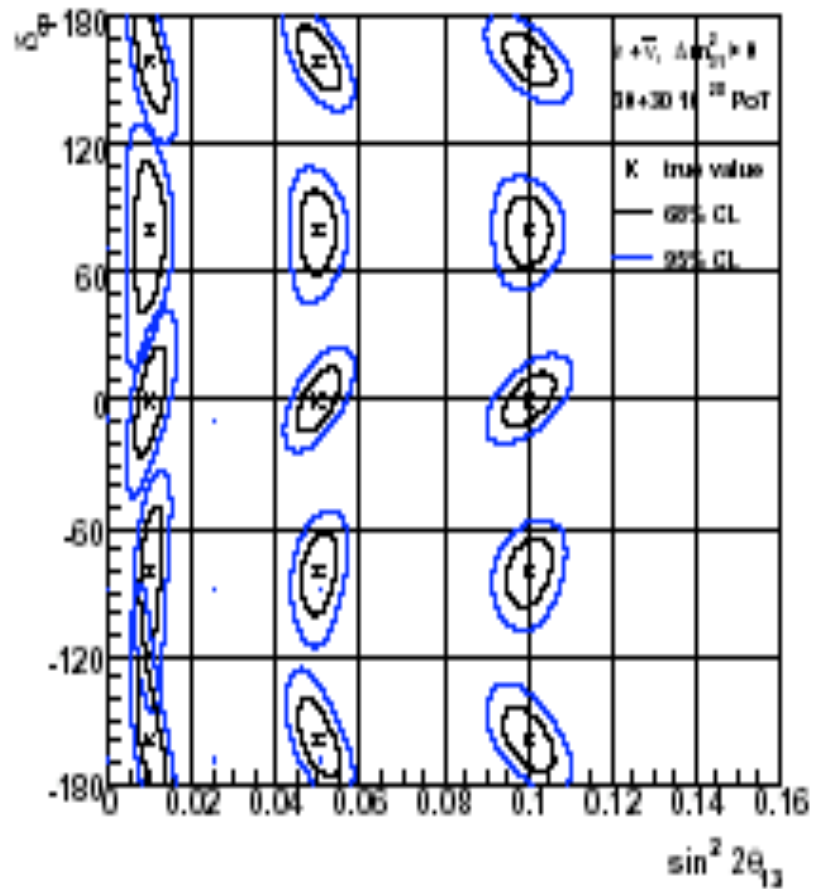
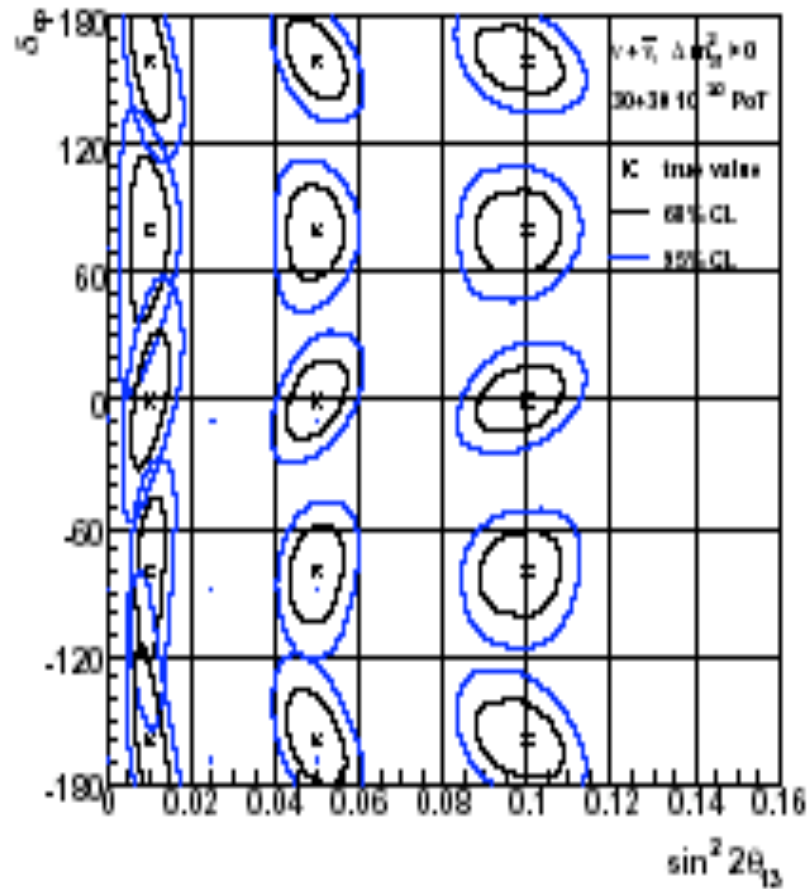
$\bar{\nu}$



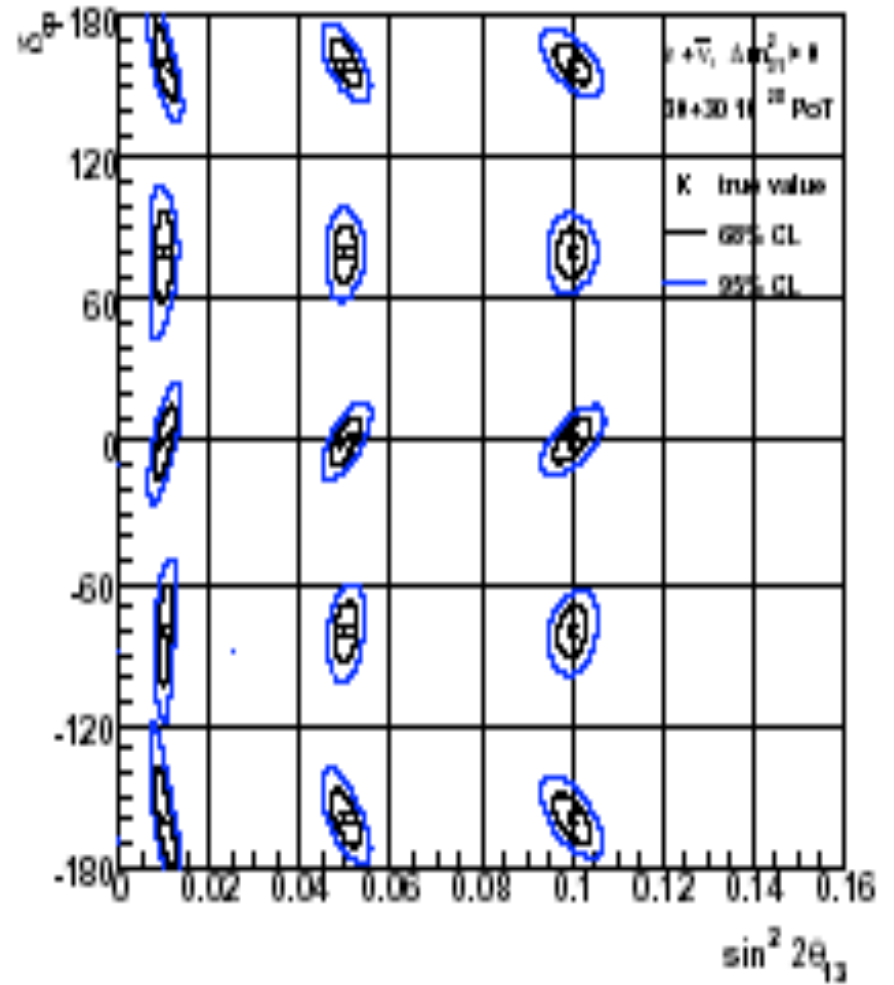
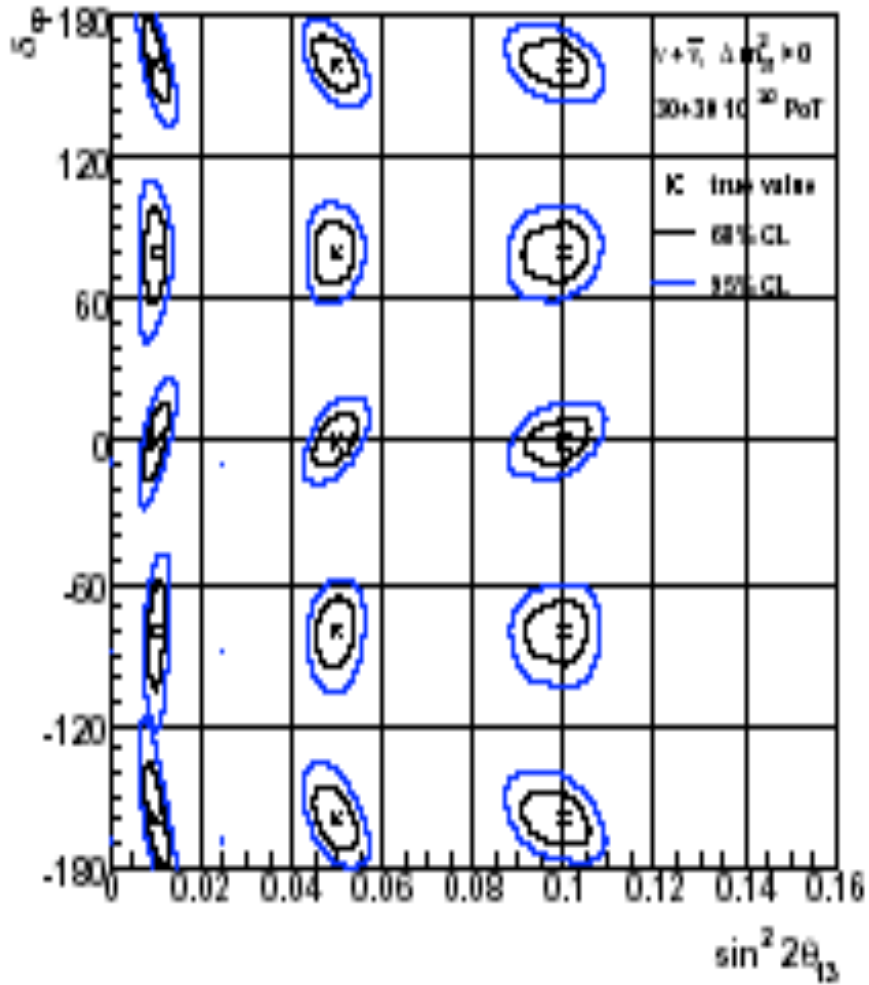
# Liquid Argon FNAL-Homestake



# Water Cerenkov CP Phase Sensitivity



# Liquid Argon: CP Phase Sensitivity



ii) **Proton Decay** (Gauge Boson Mediated)

$(X^{\pm 4/3}, Y^{\pm 1/3})$ :  $\tau(p \rightarrow e^+ \pi^0) \geq 10^{34} \text{yr}$  SuperK Goal

SuperK 22.5Kton H<sub>2</sub>O Fiducial Vol.

Next Generation  $\rightarrow 10^{35} \text{yr} \rightarrow > 300 \text{Kton H}_2\text{O}$

SUSY GUTS  $\tau(p \rightarrow e^+ \pi^0) \approx 10^{35} (m_\chi / 10^{16} \text{GeV})^4 \text{yr}$

Other decay modes  $p \rightarrow K^+ \nu, \dots$

Egs. UNO Proposal 500Kton H<sub>2</sub>O (22xSuperK)  
Homestake 300Kton H<sub>2</sub>O (Phase I) Modular  
(Cost  $\approx$  \$1M/kton)

Also Does: Magnetic Monopoles (GUT  $10^{18} \text{GeV}$ )  
(Catalyze Proton Decay  $p + M \rightarrow e^+ + M$ )  
Neutron-Antineutron Osc. ( $10^9 \text{sec}$ )  
Virtual Black Hole Proton Decay...

( $\nu$  CP Violation & Proton Decay  $\rightarrow 300 \text{kton H}_2\text{O}$ )

## 4. Outlook

We can advance:  $\nu$  CP Violation,  $\theta_{13}$ , Hierarchy,...

- Atmospheric  $\nu$ , Solar(?)
- 100,000 supernova  $\nu$  events (if in our galaxy)!
- Observe relic supernova  $\nu$  (universe history)!
- Exotic effects: sterile  $\nu$ , extra dim. dark energy...
- Proton decay,  $n$ - $\bar{n}$  osc.,...magnetic monopoles
- Potential for major discoveries is great!
- Requires Big Detector: 300kton  $H_2O$  or equivalent
- 50 yrs of physics investment! National Program

# Fermilab Activities

- What does Fermilab do after the LHC starts?
- (Great Hope - ILC  $e^+e^-$  Collider ( $\mu^+\mu^-$  Collider?))

In the meantime? New Working Group Reports  
Project X Option- 8GeV proton linac (ILC R&D?)

MI: 2MW at 50GeV provides nice neutrino beam

Doable! Must Do!

**(START AS SOON AS POSSIBLE!)**

**The Future Won't Wait**